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DMIC

review OF RECENT DEVELOPMENTS

Mechanical Properties of Metals

J. E. Campbell • February 3, 1967

LOW-TEMPERATURE PROPERTIES

As part of an extensive NASA program to evaluate materials for liquid-hydrogen fuel tanks that will be subjected to meteoroid impact in space, Douglas engineers have used biaxially stressed specimens of 2219-T87 aluminum alloy and Ti-5Al-2.5Sn (ELI) alloy which were cooled with liquid hydrogen as targets for hypervelocity pellets.(1) Boundary conditions were determined for biaxial hoop stress and projectile kinetic energy for certain types of pellets and panel thicknesses for "puncture only" and catastrophic failure of these alloys at -423 F. Use of a normalized master curve to show this relationship for both alloys is illustrated in Figure 1.

In order to obtain background data on the fracturing characteristics of the two alloys, uniaxial fracture-toughness tests and biaxial (bulge) tests were made on precracked specimens at -423 F. In addition to the precracked specimens, uniaxial and biaxial specimens containing flaws that were produced by puncturing with hypervelocity projectiles also were tested at -423 F. Average data for the uniaxial test specimens are shown in Table 1. These data indicate that the flaws produced by simulated meteoroid impact are not as severe as fatigue cracks. Biaxial toughness was calculated from the uniaxial data, and results of biaxial tests indicated good correlation. The two alloys evaluated in the program apparently are suitable for liquid-hydrogen storage vessels in meteoroid environments, since they can tolerate small hypervelocity punctures at -423 F without catastrophic failure.

Determination of tensile properties and fracture toughness of 2219-T87 aluminum alloy at cryogenic temperatures also has been the subject of a research program at Frankford Arsenal.(2) Specimens for this program were obtained from 1/2 inch

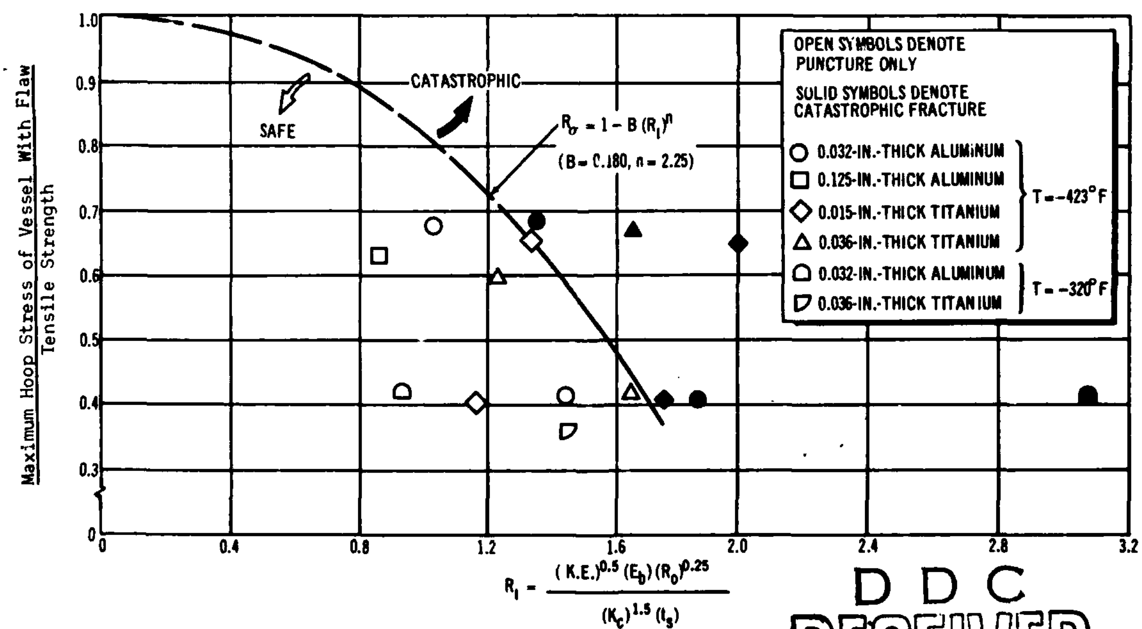

FIGURE 1. MASTER CURVE - RESULTS OF BIAXIAL PANEL-POINT-LOAD TESTS [BEHAVIOR OF 2219-T87 ALUMINUM AND 5Al-2.5Sn (ELI) TITANIUM AT LH_2 AND LN_2 TEMPERATURES](1)

Note: K.E. = kinetic energy, E_b = bulk modulus, Ro = characteristic length of projectile, t_s = panel thickness.

TABLE 1. UNIAXIAL TEST DATA FOR PREFLAWED TENSILE SPECIMENS TESTED AT -423 F[1]

Alloy	Panel Type	Thickness, in.	K_c,[a] ksi $\sqrt{in.}$	R_p[b]
2219-T87	Center fatigue crack	0.032	100	2.88
		0.125	96	3.38
	Center impact flaw	0.032	112	3.90
		0.125	101	3.35
Ti-5Al-2.5Sn (ELI)	Center fatigue crack	0.015	113	0.70
		0.036	159	1.63
	Center impact flaw	0.015	163	2.34
		0.036	176	2.58

Note: Specimens were 12 inches wide in the test section and were obtained from the transverse direction.

(a) K_c calculations were based on crack length at beginning of unstable crack propagation. The center impact flaw obviously is not equivalent to the center fatigue crack.

(b) R_p is notch resistance factor in Christensen-Denke equation.

and 1 inch plate. Tensile properties to -423 F are plotted in Figure 2, and fracture-toughness data are plotted in Figure 3. For the latter data, crack propagation was in four orientations as shown in the inset in Figure 3. Because of its good strength and toughness from room temperature to -423 F, the alloy is being considered for cryogenic fuel tankage.

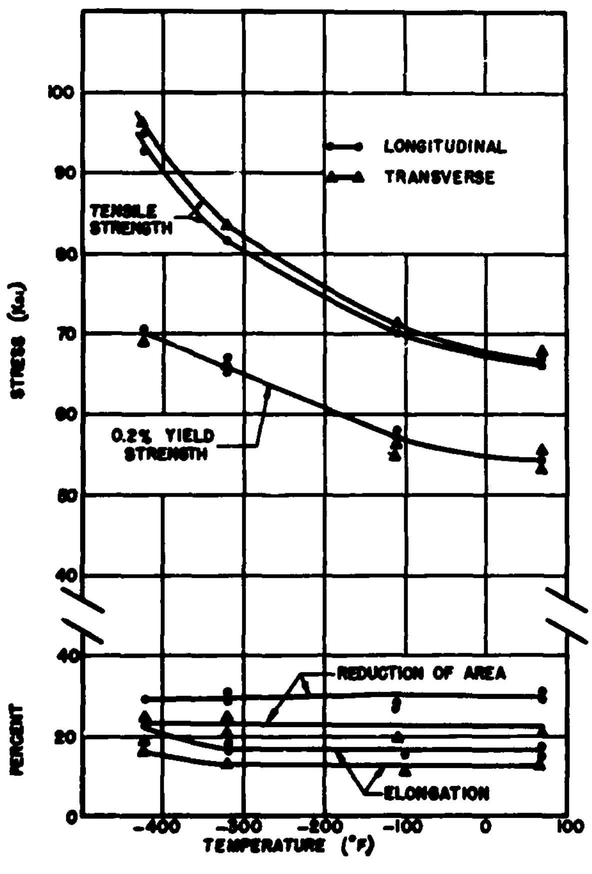

FIGURE 2. TENSILE PROPERTIES OF 1-INCH-THICK PLATE OF 2219-T87 ALUMINUM ALLOY AS A FUNCTION OF TESTING TEMPERATURE[2]

FRACTURE TESTING

Draft copies of a "Recommended Practice for Plane-Strain Fracture Toughness Testing of High-Strength Metallic Materials Using a Crack-Notch Bend Specimen" have been submitted to members of Subcommittee I of ASTM Committee E-24 for letter ballot.[3] In this recommended practice, the procedures for determining required specimen sizes, loads for critical crack propagation, determination of validity of data, etc., have been selected with the intent of making this test as widely applicable as possible for obtaining plane-strain data for high-strength alloys. The procedure is not limited to specimens for which pop-in occurs as long as other requirements of the test are satisfied to indicate that plane-strain fracturing has occurred at the critical load. Approval of this recommended practice will culminate a number of years of effort by the Committee and Subcommittee to establish a recognized plane-strain testing procedure. Other types of specimens such as the single-edge-notch and center-crack specimens will also be considered for recommended practices.

A series of specimens of maraging steel (18Ni, 250 grade, CEVM) were prepared and tested at the Lewis Research Center.[4] These tests were made according to the recommended practice discussed above using specimens 1.80 inches thick, 3.75 inches wide, and 18 inches long with a span of 15 inches in the three-point loading fixture. The specimens were aged for 6 hours at temperatures from 700 to 1000 F. The data are as follows:

Aging Temperature, F	Yield Strength, 1000 psi	K_{Ic}, 1000 psi $\sqrt{in.}$
700	174	147
750	204	137
800	226	97
850	253	74
900	259	84
950	252	85
1000	232	86

From the standpoint of fracture toughness, overaging at temperatures slightly above 900 F might be preferred to provide assurance that no parts of a given structure are underaged.

In a study of fracture toughness of nonferrous alloys in 4-inch-thick sections at the Navy Marine Engineering Laboratory, four-point bend specimens 3.875 inches square and 27 inches long were evaluated.[5] The data of interest are for specimens of 7075-T6 aluminum alloy from 4-inch-thick plate and for 2024-T4 aluminum alloy from a 4-inch-square extrusion. The data are as follows:

Alloy	K_{Ic}, 1000 psi $\sqrt{in.}$
2024-T4	49
7075-T6	35

Center-notched fracture-toughness specimens 1/8 inch thick by 3 inches wide and 1 inch thick by 20 inches wide have been used in evaluating aluminum-alloy plate at Alcoa Research Laboratories.[6] The smaller specimens had notch-tip radii equal to or less than 0.0005 inch. Average fracture-toughness data for the 20-inch-wide specimens are as follows:

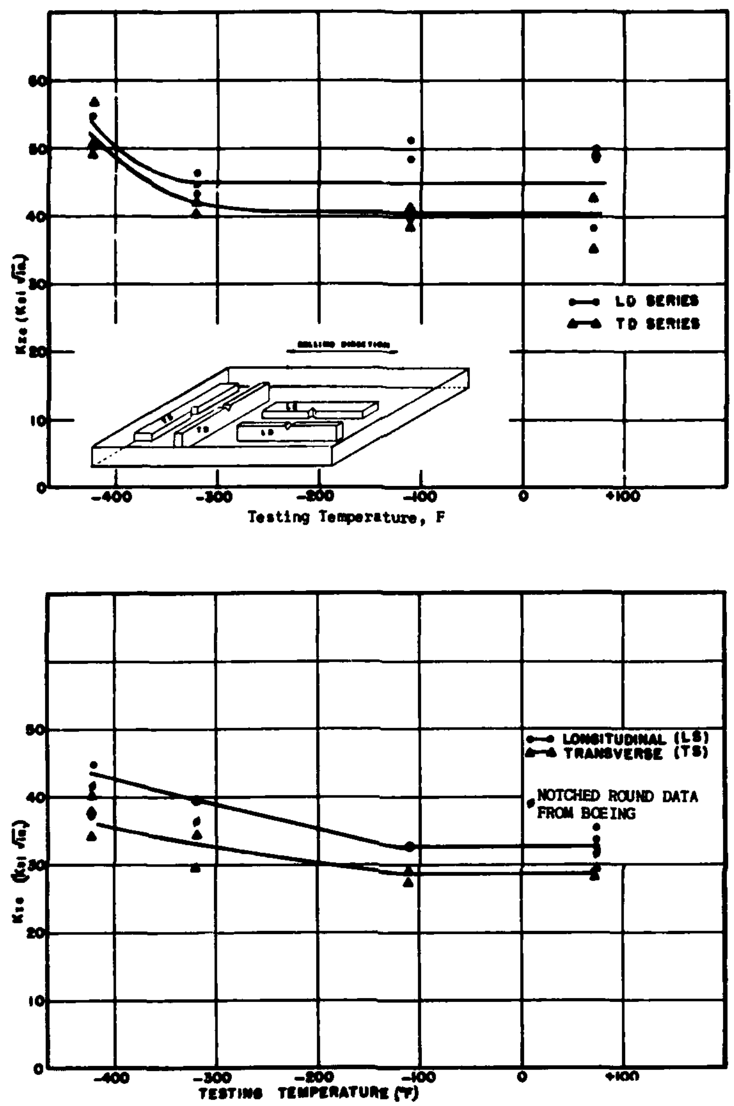

FIGURE 3. PLANE-STRAIN FRACTURE TOUGHNESS OF 1-INCH-THICK 2219-T87 ALUMINUM-ALLOY PLATE(2)

Alloy	Minimum Yield Strength, 1000 psi	K_{Ic}, 1000 psi $\sqrt{in.}$ Longitudinal	Transverse
2219-T851	44.0	41.8[a]	37.1[a]
7075-T7351	56.0	37.7	32.7
7075-T651	66.0	30.8	27.0
7079-T651	63.0	30.8	27.0
2024-T851	56.0	26.1	21.7
7001-T75	66.0	24.1	22.2
2020-T651	70.0	21.1	18.9

(a) Approximate values for 2219-T851 alloy.

These values are about the same or slightly higher than those obtained for the smaller fatigue-cracked specimens. Rate of propagation of fatigue cracks also was studied for this series of alloys.

The overall rating in descending order is as follows:

7079-T651
7001-T75
7075-T651
2024-T851
7075-T7351
2219-T851.

Specimens of Alloy 2020-T651 had the lowest rate of fatigue-crack propagation at low stress-intensity values and the highest rate at high stress-intensity values as compared with the other alloys. Furthermore, final fracture occurred in specimens of 2020-T651 at the lowest stress-intensity values, reflecting the low fracture toughness of this alloy.

In a study of the effect of tempering temperature on fracture toughness of AFC-77 stainless-steel alloy at the Air Force Materials Laboratory, center-notch, single-edge-notch, and precracked Charpy specimens were used.[7] Optimum properties at room temperature were obtained following the 700 F tempering treatment. This treatment resulted in 182,000 psi yield strength and 65,000 psi $\sqrt{in.}$ value for K_{Ic} (plane-strain fracture toughness parameter) for longitudinal specimens. The complete heat treatment for this alloy is to heat to 1900 F, hold 1 hour at temperature, oil quench, cool to -110 F for 1/2 hour, and temper for 2 + 2 hours at the designated temperature. There was excellent agreement between the results for the center-notch and single-edge-notch specimens for the K_{Ic} values. The precracked Charpy data provided information on the transition-temperature which was above room temperature for specimens tempered at 800 F and higher.

HIGH-STRAIN-RATE TESTING

Since very high transient pressures had been experienced in tests of the Apollo service module reaction control system engine when this engine was started, a program was initiated at Marquardt to determine the effects of the high strain rates on the properties of the materials of the combustion chamber.[8] The purpose of the program was to evaluate selected refractory alloys, both coated and uncoated, under the environmental and loading conditions to which the engine would be subjected on ignition. Round tensile specimens were tested at the usual slow rates at -100 F, room temperature, and 2500 F and at high rates at -100 F and room temperature. A condensation of the results of the tensile tests is presented in Table 2. The high strain rates were the same order of magnitude as those experienced by the chamber wall during maximum ignition pressure. Data in the table show the strength/elongation relationship. The data indicate that for the ductile materials, the strength was 50 to 100 percent higher when tested at the high strain rate as compared with the results at the low rate. The molybdenum specimens were partially embrittled because of partial recrystallization during the coating process. This caused low ductility in the molybdenum specimens that were tested at -100 F and at the high strain rates. The vacuum thermal cycling hydrogen exposure had no detrimental effect on the high-strain-rate data for the tantalum-base alloy and the two columbium-base alloys.

In full-scale combustion-chamber tests, molybdenum chambers coated with Durak B fractured in a brittle fashion from 3700 to 6700 psi at pressure-rise rates of 180 to 250 psi/microsecond. However, chambers of 90Ta-10W with R512 coating, columbium C-103 with Durak KA coating, and columbium C-103 with tungsten plus R508C coating withstood 15,000 psi chamber pressure at 150 to 250 psi/microsecond pressure rise with significant dynamic strain without failure. This is indicative of some degree of correlation between the high-strain-rate tension test data and the results of the full-scale dynamic pressure test data.

TABLE 2. TENSILE PROPERTIES OF REFRACTORY ALLOYS AT LOW AND HIGH STRAIN RATES[8]

Data are presented as tensile strength in 1000 psi/elongation in percent in 1 inch for specimens of 0.125-inch diameter in the test section.

Material and Coating	Low Strain Rate[a] -100 F	Low Strain Rate[a] RT	Low Strain Rate[a] 2500 F[c]	High Strain Rate[b] -100 F	High Strain Rate[b] RT	High Strain Rate[b] Vacuum Thermal Cycle,[d] -100 F	High Strain Rate[b] 15% H_2,[e] -100 F	High Strain Rate[b] 30% H_2,[e] -100 F
Molybdenum + Durak B[f]	92/0	80/27	8/8	73/4	80/1	70/1	74/0	68/0
90Ta-10W + R512[g]	110/20	92/25	23/20	181/24	160/26	177/25	200/22	171/24
C-103 + Durak KA[h]	79/21	62/28	10.5/18	119/33	141/30	121/24	117/22	114/22
C-103 + W + R508C[i]	88/18	68/18	12/3	140/16	130/23	150/18	168/17	153/19
C-129Y + Durak KA[j]	102/21	86/21	17/14	151/16	151/25	177/18	172/16	182/15

(a) Low strain rate: 0.005 in./in./min to 0.2 percent offset (elastic strain); 0.05 in./in./min to fracture (plastic strain).
(b) High strain rate: 100 to 250 in./in./sec (elastic strain); 500 in./in./sec to fracture (plastic strain).
(c) Self-resistance heating in air.
(d) Two cycles each consisting of heating to 2500 F in 2 hours, holding 1/2 hour, furnace cooling to room temperature, removing from vacuum, cooling to -100 F, holding 1 hour, warming to room temperature.
(e) Held 1 hour at 1400 F in argon-hydrogen gas mixture.
(f) Partial recrystallization of molybdenum as a result of coating application which is a pack cementation disilicide.
(g) Coating is slurry-applied disilicide with vacuum diffusion.
(h) Cb-10Hf-1Ti-1Zr with pack cementation disilicide plus thermal conditioning.
(i) Cb-10Hf-1Ti-1Zr with vapor-deposited tungsten and vacuum-diffused aluminide.
(j) Cb-10W-10Hf with pack cementation-applied disilicide.

PROPERTIES OF 2618-T61 ALUMINUM ALLOY

Hand-forged billets of 2618-T61 aluminum alloy were evaluated in a program at the Columbus Division of North American Aviation, Inc., to determine the tension, notch-tension, compression, shear, bearing, fracture-toughness, creep, fatigue, stress corrosion, and thermal-stability properties of the alloy for use in MIL-HDBK-5 data presentation.(9) At 400 F, specimens from the short-time tests retained about 80 percent of the room-temperature strength. Stresses exceeding the yield stress were required for appreciable creep to occur at 250 F, and stresses of about 75 and 50 percent of the yield stress at temperature were required for 1 percent creep in 1000 hours at 325 and 400 F. Plane-strain fracture toughness in the longitudinal direction was similar to 7075-T6 alloy, but near the surface and at the quarter-thickness locations, fracture toughness in the long-transverse direction was generally lower than for corresponding data for the 7075-T6 alloy Results of stress-corrosion tests indicated that the 2618-T61 alloy is susceptible to stress-corrosion cracking in the long transverse and short transverse directions when stressed to 75 percent of the yield strength. The suggested presentation for MIL-HDBK-5 is shown in Table 3.

TABLE 3. SUGGESTED DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2618 ALUMINUM-ALLOY HAND-FORGED BILLET(9)

Alloy	**2618**	
Form	**Hand Forged Stock**	
Condition	**-T61**	
Thickness, (in)	**< 4 Inches**	
Cross-sectional area, (in^2)	**> 18, ≤ 44**	
Basis	**A**	**B**
Mechanical Properties:		
F_{tu}, Ksi - L	59	60
LT	56	58
ST	54	57
F_{ty}, Ksi - L	44	46
LT	43	45
ST	42	45
F_{cy}, Ksi - L	47	50
LT	43	47
ST	43	47
F_{su}, Ksi - L	35	38
LT	37	39
ST	35	37
F_{bu}, Ksi (e/D=2.0) - L	112	117
LT	114	119
F_{by}, Ksi (e/D=2.0) - L	78	83
LT	79	84
e, Percent - L	6	8
LT	4	5
ST	4	5
E, 10^6 psi	10.3	
Ec, 10^6 psi	10.6	
Physical Properties: (1)		
ω, lb/in^3	0.100	
C, BTU/(lb) (°F)	0.23 (at 212°F)	
K, BTU/ (hr) (ft^2) (°F)/ft	90.0 (at 77°F)	
α, 10^{-6} in/in/°F	12.3 (68° to 212°F)	

(1) Data not determined during this program, values are from MIL-HDBK-5

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